日本建築学会計画系論文集　第561号，21-29，2002年11月
J. Archit. Plann. Environ. Eng., AIJ, No. 561, 21-29, Nov., 2002

CONVECTIVE HEAT TRANSFER COEFFICIENTS AND CLOTHING INSULATIONS FOR PARTS OF THE CLOTHED HUMAN BODY UNDER AIRFLOW CONDITIONS

気流下の着衣人体における各部位の対流熱伝達率と着衣抵抗

Masayuki OGURO, Edward ARENS**, Richard de DEAR***, Hui ZHANG**** and Tadahisa KATAYAMA******
大黒雅之，エドワード アレンズ，リチャード デディア，ウイ チャン，片山忠久

Convective heat transfer coefficients for each part of the clothed human body were evaluated under airflow conditions and compared to those of nude body. This was done by measuring clothing surface temperatures on a seated and standing manikin using an infrared-imaging radiometer. The convective heat transfer coefficients for the clothed manikin were larger than for the nude manikin. The difference could be 100 to 200% for some individual parts, and for the overall body the difference was 30 to 50%. These results were consistent for both standing and sitting postures, or for facing upwind and facing downstream, although slightly larger differences between clothed and nude could be seen when the manikin was sitting and facing upwind than in the other conditions. Clothing insulation for each part was also estimated. Some differences between standing and sitting were observed at the body part level. However for the whole body the difference was small. Regression models for convective heat transfer coefficients and clothing insulation for all body parts were presented for use in human thermal modeling.

Keywords : *convective heat transfer, clothing insulation, infra-red thermography, human body, thermal comfort, airflow*
対流熱伝達，着衣抵抗，熱画像，人体，熱的快適性，気流

1. INTRODUCTION

Clothing insulation under calm condition for the whole human body is already estimated for many kinds of clothing and available in many standards or handbooks such as ASHRAE FUNDAMENTALS [1] and ISO-9920[2] etc. Also there are many studies on local convective heat transfer for human body under calm or airflow conditions.[3)~7)] However there are few studies that tried direct measurement of the convective heat transfer and clothing insulation at the body part level by measuring average clothing surface temperature. Danielson[8] measured local convective heat transfer on clothing surface and local clothing insulation for a standing male subject by using a special device that can measure local heat flux and surface temperature. However the data are limited only to low air speed for a standing subject. This paper provides the results for both standing and sitting postures under airflow from 0.2 to 5.5 m/s based on measuring clothing surface temperatures. The wind speed range was determined considering the fact that there are many situations where the evaluation of thermal environment under airflow is required. For example, the outdoor environments which usually have faster airflow than indoor environments, room environments controlled by personal air-conditioning systems that have air diffusers in the vicinity of occupants, room environment in buildings which employ natural ventilation, and so on. This paper is the second of two describing direct measurements of those data for each part of the body. The previous paper (Oguro[9], 2001) described clothing insulation and dry heat transfer for a standing manikin under airflow. The dry heat transfer coefficients included radiative heat transfer coefficients. This paper provides convective heat transfer coefficients for both standing and sitting manikin by subtracting out the radiative heat transfer coefficients from the dry heat transfer coefficients. The clothing insulation is also described.

2. METHODOLOGY

(1) Direct method for estimating clothing insulation Heat transfer between skin surface and the clothing for each part of the body can be described by the following equation, which is the same as for the whole body (ASHRAE FUNDAMENTALS,[1] 1997).

* Taisei Corporation, Dr. Eng. 大成建設㈱ 工博
** Prof., Center for Environmental Design Research, Univ. of California, Ph. D.
*** Assoc. Prof., Division of Environmental and Life Sciences, Macquarie University, Ph. D.
**** Center for Environmental Design Research, Univ. of California, M. Eng.
***** Prof., Dept. of Energy and Environmental Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Dr. Eng. 九州大学大学院総合理工学府環境エネルギー工学専攻 教授・工博

$Q_t = [1/(0.155\ I_{cl})]\ (t_s - t_{cl}) A_m$ (W) (1)

Where, Q_t: dry heat loss for each clothed segment (W), I_{cl}: intrinsic clothing insulation for each clothed segment (clo)
t_s: skin surface temperature of each nude segment (°C), t_{cl}: clothing surface temperature of each clothed segment (°C)
A_m: skin surface area of each nude segment (m^2)

In this study t_{cl} means average clothing surface temperature measured by an infrared imaging radiometer set away from the manikin, i.e., t_{cl} is apparent average surface temperature for apparent surface area and not the true average surface temperature for spread-out clothing surface area. Griffith[10] (1995) recently proposed a fairly accurate (±0.5 °C) technique for measuring surface temperatures using infrared thermography. As expected from Eq.(1) or Eq.(2) in the following section, ±0.5 °C means ±10% difference in clothing insulation or heat transfer coefficient for 5.0°C in temperature difference. Using this approach, by measuring the clothing surface temperature t_{cl}, using infrared thermography, one can estimate I_{cl} directly from Eq. (1). This method is referred to in this paper as the 'direct method'.

(2) Estimation of convective heat transfer coefficients for clothed body parts Assuming a uniform temperature field in which surrounding wall surface temperatures are the same as the ambient air temperature, the heat transfer between the clothing and its surrounding environment for each part of a manikin can be described by the following equation, which is the same as for the whole body.

$Q_t = h_{cl}\ (t_{cl} - t_o) f_{cl} A_m$ (W) (2)
$h_{cl} = h_c + h_r$ ($W/m^2/K$) (3)

Where, Q_t: dry heat loss for each clothed segment (W), h_{cl}: dry heat transfer coefficient for each clothed segment ($W/m^2/K$), h_c: convective heat transfer coefficient for each clothed segment ($W/m^2/K$), h_r: radiative heat transfer coefficient for each clothed segment ($W/m^2/K$), t_o: ambient air temperature or mean radiant temperature (°C), f_{cl}: clothing area factor (no dimension)

Using Eq. (2), by measuring clothing surface temperature and clothing area factor, the dry heat transfer coefficient on clothing for each clothed body part can be calculated. Further by subtracting the radiative heat transfer coefficient from that, one can obtain the convective heat transfer coefficient for each body part.

Strictly speaking, Eq.(1) and Eq.(2) should only be applied to non-permeable clothing, in which there is no convection bypassing or permeating the insulation layer. However in this study, those standard equations were applied to a set of typical permeable clothing. Thus I_{cl} and h_{cl} estimated in this study include some effect effects of heat loss by air penetration

(3) Estimation of radiative heat transfer coefficients for clothed body parts Radiant heat transfer for each part of the human body has to include the radiation heat exchange between the body parts. However, under the conditions where the surface temperature differences between all the segments are small, i.e., practically heat transfer between the segments is negligible, the following formula (ASHRAE FUNDAMENTALS,[1] 1997) for whole human body can be used for each segment.

$h_r = 4\ \varepsilon\ \sigma\ f_{eff}\ \{273.2 + (t_{cl} + t_r)/2\}^3$ ($W/m^2/K$) (4)

Where, h_r: radiation heat transfer coefficient for each segment ($W/m^2/K$), ε : emissivity for each segment (nd), σ :Stefan-Boltzmann constant ($W/m^2/K^4$), f_{eff}: effective radiation area factor for each segment (nd),
t_{cl}: surface temperature of the segment (°C), t_r: mean radiant temperature for each segment (°C)

When mean radiant temperature equals ambient air temperature, by measuring emissivity, clothing surface temperature and effective radiation area factor, the radiative heat transfer coefficient on clothing for each clothed body part can be calculated.

3. MEASUREMENT PROCEDURE

The measurement procedure used in this study was already described in the previous paper[9]. Thus the outline of the procedure will be presented here.

(1) Thermal Manikin A skin-temperature-controlled thermal manikin was used for measuring the clothing insulation and dry heat transfer coefficient for each body segment. This manikin was developed to evaluate asymmetric thermal environment by measuring the heat loss at each part of the body (Tanabe[11], 1994). The 16 body segments and their respective surface areas are listed in Table 1. The effective radiation area factor for each segment both for standing and sitting postures is estimated by Oguro (Oguro[12),13)], 2001) as shown in Table 2. The height of the manikin is 1.6m.

(2) Clothing The clothing ensemble used in this study is a set of casual clothing items for mid season. These items are: panties and bra, 100% cotton shirt with long sleeves, 100% cotton trousers, socks and shoes. In addition, in this study a medium length hair wig for the head was employed and treated as a clothing item.

To clearly define the heat loss from the clothing surface for each segment of the body, the clothing was cinched down along the manikin segment boundaries using plastic tape. This was done to prevent lateral heat transfer between segments due to air movement underneath the clothing. Fig.1 shows a picture of the clothed thermal manikin used in this study.

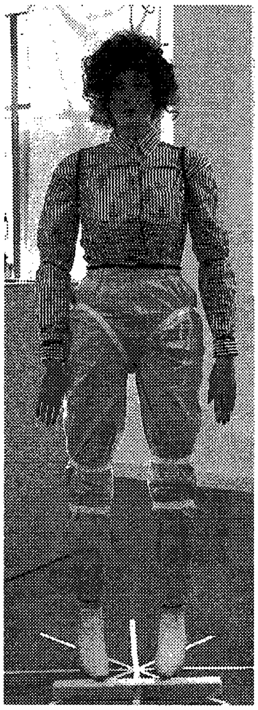


Figure 1 Thermal manikin

(3) Measurement of clothing area factor Clothing area factor is usually measured as an average of projected area ratios between nude and clothed human body measured at several main angles (ISO9920[15)], 1995). In this study, pictures were taken with a 35mm camera with a 50mm lens from 8 directions, i.e., horizontally every 45 degrees, around the manikin at the distance of 2m from the manikin. Averaged ratios between nude and clothed were used as clothing area factors for each body part in subsequent analyses.

(4)Wind tunnel test procedure

The wind tunnel The manikin was set in a wind tunnel with a test section 1.5m high and 2.1m wide. At seven meters upwind of the test section, a large cylindrical drum (1.0 m tall and 0.5m in diameter) was installed to generate some large-scale eddies in the airflow (This resulted in 2.3 to 13.1% turbulence intensity across the range of wind speed measurements).

Wind tunnel anemometry There were 10 separate anemometer measurements for a full sweep of the tunnel cross section. Their heights above the floor of the wind tunnel were: 0.02, 0.15, 0.28, 0.41, 0.54, 0.66, 0.79, 0.92, 1.05, and 1.18m. The mean values obtained at adjacent measurement points were used.

Wind tunnel temperature sensors Four temperature probes were mounted near the manikin at different heights within the wind tunnel's working section. The probes were thermistors mounted at the tips of 30-cm-long shafts. The four measuring heights were: 0.10, 0.50, 0.90, and 1.20m. All subsequent analyses performed on each manikin body segment were based on measurements from the nearest of these temperature probes.

The surface temperature measurement An infrared imaging radiometer (Inframetrics MODEL 760) was used to measure the temperature of the clothing surface on the manikin. A thin film with known emissivity of 0.90 was employed as a reference emitter and 4 pieces of the film were set near the air temperature sensors in the wind tunnel. The surface temperature of the film was assumed to be very close to the air temperature. Then the surface temperatures measured by the radiometer were corrected by using the difference of the surface temperature of the film measured by the radiometer and the air temperature measured by the thermistor. Prior to the actual measurement, the emissivity of the film and main clothing items was measured by using a radiometer. The emissivity of the shirt

Table 1 Surface areas of the nude manikin

Body Segment	Surface Area (m²)
Back	0.128
Chest	0.138
Head	0.117
Left Arm	0.050
Left Foot	0.043
Left Hand	0.038
Left Leg	0.090
Left Upper Arm	0.076
Left Thigh	0.160
Right Arm	0.051
Right Foot	0.042
Right Hand	0.036
Right Leg	0.090
Right Upper Arm	0.073
Right Thigh	0.166
Pelvic Region	0.170
Whole Body	1.469

Table 2 Effective radiation area factor

Body Segment	Standing(nd)	Sitting (nd)
Back	0.90	0.96
Chest	0.88	0.78
Head	0.91	0.90
Left Arm	0.83	0.80
Left Foot	0.87	0.83
Left Hand	0.80	0.77
Left Leg	0.93	0.84
Left Upper Arm	0.82	0.80
Left Thigh	0.86	0.79
Right Arm	0.78	-
Right Foot	0.91	-
Right Hand	0.78	-
Right Leg	0.89	-
Right Upper Arm	0.90	-
Right Thigh	0.85	-
Pelvic Region	0.86	0.86
Total	0.85	0.80

Table 3 Clothing area factor

Body Segment	Standing(nd)	Sitting (nd)
Back	1.11	1.16
Chest	1.03	1.04
Head	1.51	1.57
Left Arm	1.21	1.25
Left Foot	1.41	1.38
Left Hand	1.00	1.00
Left Leg	1.25	1.11
Left Upper Arm	1.24	1.23
Left Thigh	1.08	1.06
Right Arm	1.21	-
Right Foot	1.31	-
Right Hand	1.00	-
Right Leg	1.28	-
Right Upper Arm	1.24	-
Right Thigh	1.14	-
Pelvic Region	1.03	1.05
Total	1.17	1.15

and trousers used in this study were estimated as 0.87 and this value was used as emissivity for all the clothing items.

Test conditions Measurements were carried out for the nude and clothed manikin for wind directed onto her front and back. The wind speed was set at 0.2, 0.5, 0.8, 1.2,2.0, 3.0 and 5m/s (only 0.8, 2.0, 5m/s for nude) for each case. Both standing and sitting postures were tested. Because the height of the wind tunnel was not enough for the manikin to stand fully erect, the insulation of the lower legs in the standing posture was not measured. For the standing tests, the knees of the manikin was bent with her unheated lower legs trailing back in a kneeling position. (Thus the data for standing posture do not include the results for legs and feet.) For the duration of measuring the clothed manikin, the air temperature was mostly between 21 and 22.5 ℃. For the duration of measuring the nude manikin, that was mostly between 20 and 21℃.

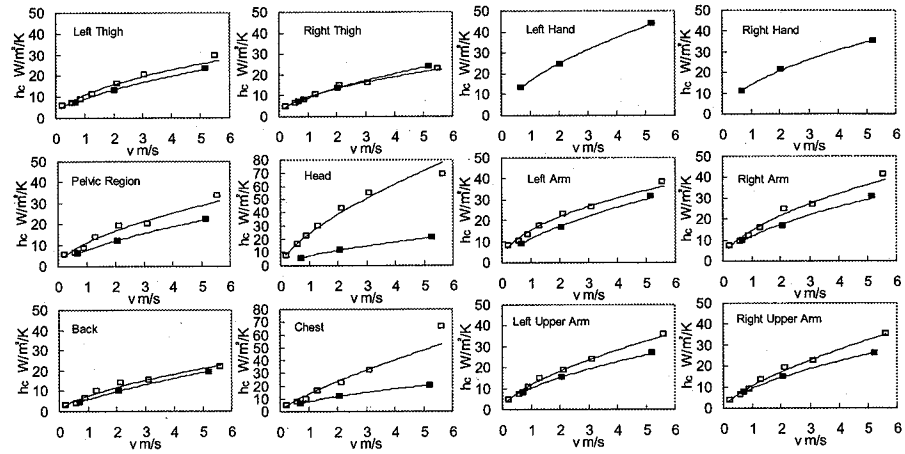


Figure 2(a) Convective heat transfer coefficients for each part of a standing manikin when the manikin faces upwind
(Open square means the results from clothed manikin and solid square means those from nude manikin)

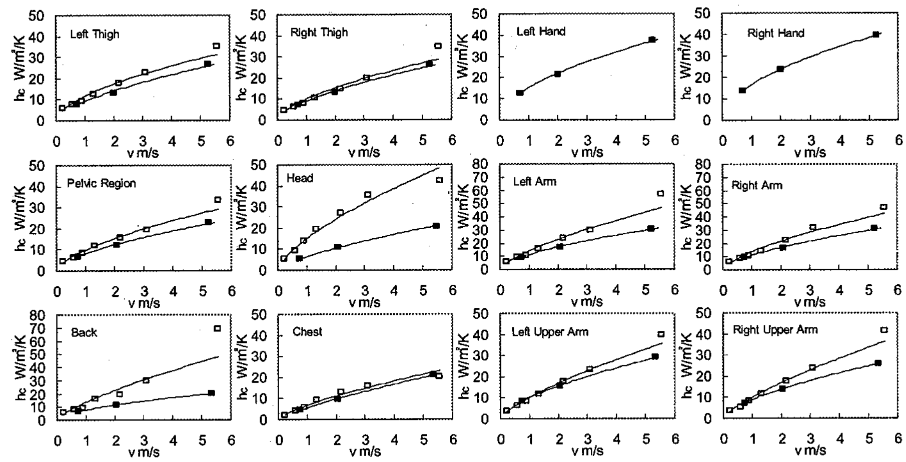


Figure 2(b) Convective heat transfer coefficients for each part of a standing manikin when the manikin faces downstream
(Open square means the results from clothed manikin and solid square means those from nude manikin)

4. RESULTS AND DISCUSSION

(1) Clothing area factor

Table 3 shows the measured clothing area factors. For the upper arm, the forearms, the hands, the thighs, legs, and the feet in sitting posture, only left side of the manikin was measured. Head, with a wig, and the feet with shoes had large clothing area factors. There were many parts that had small clothing area factors such as the chest and the thighs. This was partly due to the binding of the clothing between segments as seen in Fig.1. In total, the clothing area factor was 1.17 for standing and 1.15 for sitting (values for the right side assumed as the same values for the left side).

(2) Convective heat transfer coefficients for the standing manikin Fig.2 (a) shows the comparison between nude and clothed convective heat transfer coefficients under airflow from the front. Fig.2(b) shows the comparison of those under airflow from the back. In standing manikin, the feet and legs were not studied. For hands only those for nude manikin are shown and the same values can be used also for clothed manikin, because the hands area usually naked.

The first discussion is concerned with nude standing manikin. Considerably larger values were obtained at hands and relatively smaller values were obtained at back, chest, and head for both wind directions.

When looking at clothed standing manikin, overall the larger values than those for nude were seen. Only exceptions were at the thighs and the back/chest under the airflow from the front/back that showed almost no differences between nude and clothed. Significantly larger coefficients on clothed human body meet the results from literature (Danieleson[8], 1995). For the head and the chest/back when they faced upwind, the convective heat transfer coefficients increased up to more than twice of those for nude. The increase rate was highest at the head under the airflow from the front, as the face was naked and also the wind penetrated the wig. The reason for the high values at the chest and back when they face the wind may be mainly due to the wind penetration.

When looking at the convective heat transfer coefficients at the velocity of about 0.8m/s, the differences of those values between nude and clothed manikin, except for the head, were relatively small. This suggests that, except for the head, the convective heat transfer coefficients for the nude may be used for clothed surfaces as long as the wind speeds are low. However whenever one notices a large temperature difference between nude and clothed surfaces, the air insulation I_a from nude should not be used for the clothed manikin.

Except for a few cases such as thighs and the back/chest under the airflow from the front/back, the higher the velocity was, the higher was the difference between clothed and nude convective heat transfer coefficients. The difference was largest at the head under the wind from the front. This is probably due to air penetration, because at the back for frontal wind and at chest for rear wind, where it should have a relatively low velocity, the differences between clothed and nude are very small. Slight differences between left side and right side may be due to slight differences of those shapes and the fit of clothing.

(3) Convective heat transfer coefficients for the sitting manikin Fig.3 (a) and (b) show convective heat transfer coefficients for nude/clothed sitting manikin under airflow. Concerning the nude results, larger values were observed at hands than the others as already seen in standing manikin. The main differences from standing were as follows. 1) Slightly lager values were seen in the head, the back, and the chest. This may be due to the inclination of those parts. 2) Smaller values in the thighs and larger values were seen in the pelvic region when the manikin was facing downstream. The reason would be that the pelvic region had no obstacles underneath such as thighs and legs, and the thighs are blocked by the pelvic region when the manikin was facing the downstream. Concerning the feet and legs, convective heat transfer coefficients were as large as those for arms for both directions.

When looking at the results from clothed sitting manikin, overall the larger values than those for nude were seen as already seen in standing manikin. The main differences from standing were as follows. 1) Large differences between nude and clothed manikin were seen in the thighs when the manikin was

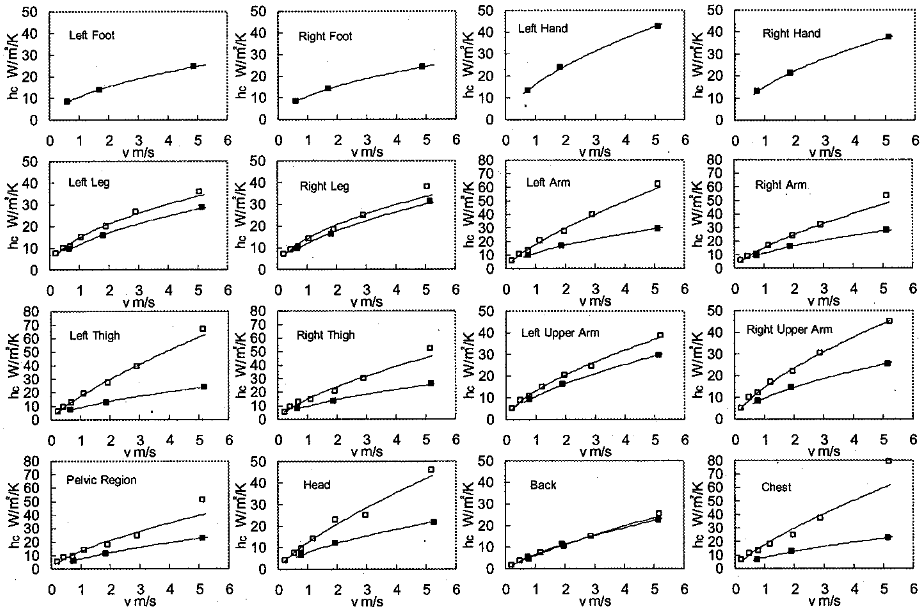


Figure 3(a) Convective heat transfer coefficients for each part of a sitting manikin when the manikin faces upwind
(Open square means the results from clothed manikin and solid square means those from nude manikin)

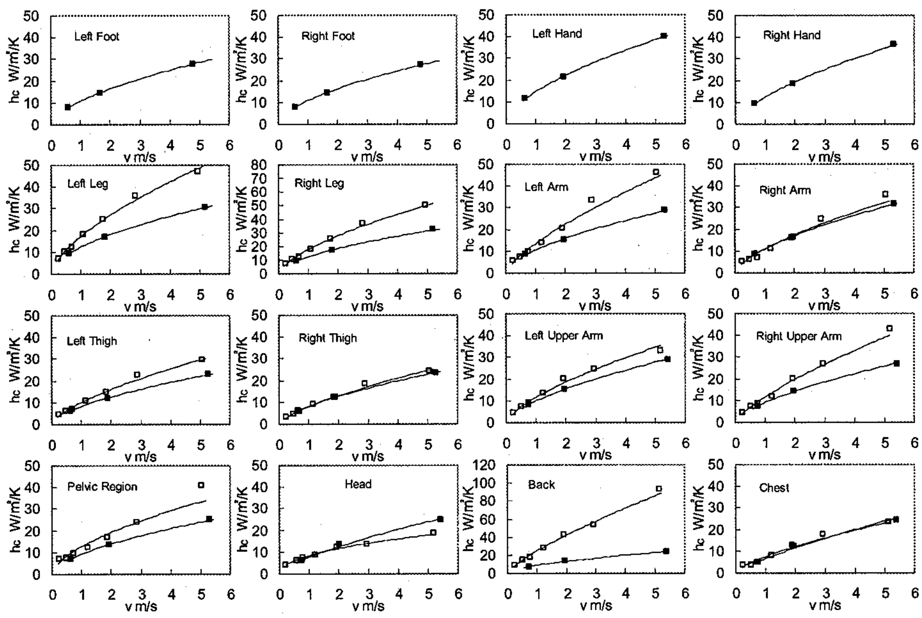
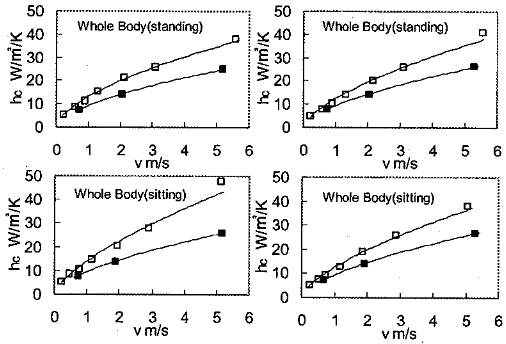


Figure 3(b) Convective heat transfer coefficients for each part of a sitting manikin when the manikin faces downstream
(Open square means the results from clothed manikin and solid square means those from nude manikin)

facing upwind. This may be partly due to significant change of the gap between left and right thighs by clothing. 2) Slow increase of the values was seen in the head when the manikin was facing downstream. This may be due to the inclination and unintentional change of the fit of the wig.

Concerning the legs, the differences between nude and clothed manikin were small when the manikin was facing unwind. On the other hand, the differences between those were rather large when the manikin was facing downstream. This may be due to the tight fit in the front and loose fit in the backside of the leg.

Fig.4 shows the results for the whole body for nude/clothed sitting/standing manikin. Overall there was no very large difference between standing and sitting or between facing upwind and facing downstream. The clothed manikin had larger convective heat transfer coefficients than nude one by 30 to 50%. Slightly larger effect of clothing was seen when the manikin was sitting and facing upwind. than the other conditions.



(a) Facing upwind (b) Facing downstream

Figure 4 Convective heat transfer coefficients for clothed and nude whole body
(Open square means the results from clothed manikin and solid square means those from nude manikin)

(4) Clothing insulation The results of clothing insulation for each part of the body for standing posture were already presented in the previous paper (Oguro[7], 2001). Thus in this paper the results for the sitting posture and the difference from the standing posture will be mainly discussed.

Fig.5 shows the comparison of clothing insulation between standing and sitting manikins when they faced upwind. Except for the back, some differences between standing and sitting were seen. The results from sitting posture had higher insulation at the thighs, the chest, and the upper arms and lower insulation at the pelvic region, the head, and the forearms.

Fig.6 shows the results for the whole. Overall there was no very large difference between standing and sitting or between facing upwind and facing downstream. Slightly larger values for the sitting manikin were seen when the manikin was facing downstream.

(5) Models for convective heat transfer coefficients and clothing insulation

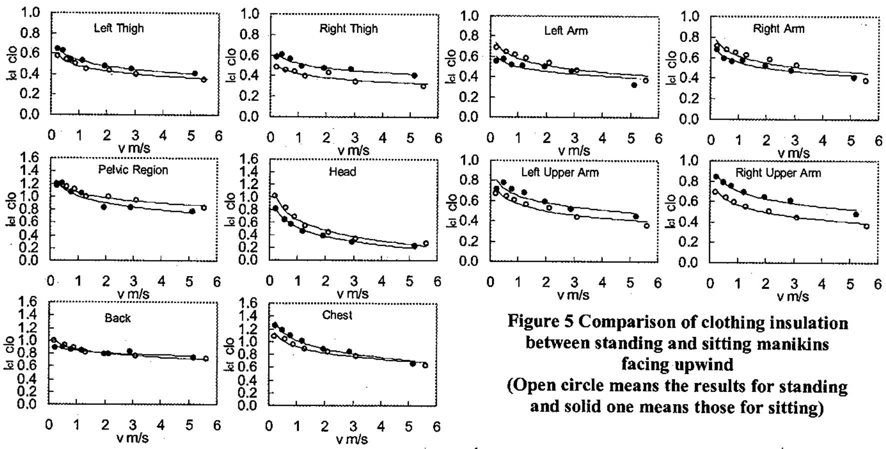


Figure 5 Comparison of clothing insulation between standing and sitting manikins facing upwind
(Open circle means the results for standing and solid one means those for sitting)

According to other studies (Danieleson[8], 1995 Ichihara[7], 1997, deDear[6], 1997), convective heat transfer coefficients can be modeled by power function of wind speed (the power of around 0.5). Good fits were also found in this model for all the part and the whole body. Table 4 to 7 show regression models for convective heat transfer coefficients. For practical purpose all the models for all the body parts for both sitting and standing postures are listed although some body parts have the same regression model each other based on the same data, e.g. feet and legs for sitting and standing posture. The model constants are defined as power function ($h_c = a(v)^b$). The exponents for most of the segments between 0.4 and 0.8 were found regardless the manikin was nude or clothed. For the whole body the exponents were between 0.60 to0.69 and there was no large difference regardless the manikin was sitting or standing, also regardless the manikin was facing upwind or downstream. Overall the large difference between nude and clothed was mainly reflected in the difference of the constant 'a'.

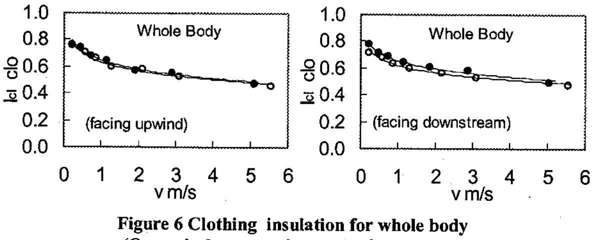


Figure 6 Clothing insulation for whole body
(Open circle means the results for standing and solid one means for sitting)

Table 8 and 9 show regression models for clothing insulation

Table 4 Models of convective heat transfer for standing manikin facing upwind

	Nude Manikin			Clothed Manikin				
Body Segment	a	b	R^2	a	b	R^2	h_{cl}/h_n in average	reference data
Back	5.86	0.74	1.00	7.67	0.63	0.95	1.30	
Chest	7.77	0.59	1.00	13.80	0.77	0.96	1.91	
Head	7.14	0.65	1.00	24.07	0.68	0.99	3.40	
Left Arm	11.40	0.60	0.99	15.46	0.50	0.98	1.33	
Left Foot	10.59	0.53	1.00	10.59	0.53	1.00	1.00	sitting
Left Hand	16.57	0.59	1.00	16.57	0.59	1.00	1.00	nude
Left Leg	11.70	0.54	1.00	14.80	0.52	1.00	1.26	sitting
Left Upper Arm	10.04	0.59	1.00	11.86	0.63	0.99	1.19	
Left Thigh	8.94	0.58	1.00	11.02	0.53	0.95	1.23	
Right Arm	11.79	0.57	0.99	14.61	0.57	0.97	1.25	
Right Foot	10.77	0.51	1.00	10.77	0.51	1.00	1.00	sitting
Right Hand	14.04	0.57	1.00	14.04	0.57	1.00	1.00	nude
Right Leg	12.03	0.57	1.00	14.24	0.53	0.97	1.18	sitting
Right Upper Arm	9.51	0.62	1.00	10.62	0.70	0.99	1.14	
Right Thigh	8.95	0.60	1.00	9.47	0.50	0.98	1.05	
Pelvic Region	7.60	0.65	1.00	11.09	0.60	0.94	1.46	
Whole Body	9.31	0.60	1.00	13.36	0.60	0.99	1.42	

Table 5 Models of convective heat transfer for standing manikin facing downstream

	Nude Manikin			Clothed Manikin				
Body Segment	a	b	R^2	a	b	R^2	h_{cl}/h_n in average	reference data
Back	7.75	0.57	0.998	13.87	0.72	0.907	1.93	
Chest	5.81	0.77	0.999	6.90	0.71	0.987	1.18	
Head	6.52	0.69	1.000	15.11	0.68	0.985	2.32	
Left Arm	11.37	0.59	0.998	14.26	0.69	0.964	1.30	
Left Foot	10.87	0.60	1.000	10.87	0.60	1.000	1.00	sitting
Left Hand	15.25	0.54	0.999	15.25	0.54	0.999	1.00	nude
Left Leg	12.42	0.55	1.000	17.32	0.64	0.979	1.42	sitting
Left Upper Arm	10.25	0.62	0.999	10.31	0.72	0.985	1.04	
Left Thigh	9.19	0.63	0.992	11.80	0.57	0.970	1.28	
Right Arm	11.05	0.61	0.994	13.78	0.66	0.963	1.27	
Right Foot	10.91	0.58	1.000	10.91	0.58	1.000	1.00	sitting
Right Hand	16.66	0.52	1.000	16.66	0.52	1.000	1.00	nude
Right Leg	12.54	0.56	0.999	17.77	0.65	0.990	1.44	sitting
Right Upper Arm	8.99	0.63	1.000	10.17	0.74	0.969	1.18	
Right Thigh	8.99	0.63	0.994	10.02	0.62	0.964	1.12	
Pelvic Region	8.16	0.61	0.996	9.99	0.63	0.972	1.24	
Whole Body	9.41	0.61	0.999	12.38	0.65	0.999	1.34	

Table 6 Models of convective heat transfer for sitting manikin facing upwind

	Nude Manikin			Clothed Manikin				
Body Segment	a	b	R^2	a	b	R^2	h_{cl}/h_n in average	reference data
Back	5.86	0.74	1.00	7.67	0.63	0.95	1.30	
Chest	7.77	0.59	1.00	13.80	0.77	0.96	1.91	
Head	7.14	0.65	1.00	24.07	0.68	0.99	3.40	
Left Arm	11.40	0.60	0.99	15.46	0.50	0.98	1.33	
Left Foot	10.59	0.53	1.00	10.59	0.53	1.00	1.00	sitting
Left Hand	16.57	0.59	1.00	16.57	0.59	1.00	1.00	nude
Left Leg	11.70	0.54	1.00	14.80	0.52	1.00	1.26	sitting
Left Upper Arm	10.04	0.59	1.00	11.86	0.63	0.99	1.19	
Left Thigh	8.94	0.58	1.00	11.02	0.53	0.95	1.23	
Right Arm	11.79	0.57	0.99	14.61	0.57	0.97	1.25	
Right Foot	10.77	0.51	1.00	10.77	0.51	1.00	1.00	sitting
Right Hand	14.04	0.57	1.00	14.04	0.57	1.00	1.00	nude
Right Leg	12.03	0.57	1.00	14.24	0.53	0.97	1.18	sitting
Right Upper Arm	9.51	0.62	1.00	10.62	0.70	0.99	1.14	
Right Thigh	8.95	0.60	1.00	9.47	0.50	0.98	1.05	
Pelvic Region	7.60	0.65	1.00	11.09	0.60	0.94	1.46	
Whole Body	9.31	0.60	1.00	13.36	0.60	0.99	1.42	

Table 7 Models of convective heat transfer for sitting manikin facing downstream

	Nude Manikin			Clothed Manikin				
Body Segment	a	b	R^2	a	b	R^2	h_{cl}/h_n in average	reference data
Back	8.80	0.59	1.00	24.81	0.77	0.99	2.96	
Chest	6.61	0.80	0.99	7.59	0.69	0.95	1.15	
Head	7.71	0.70	0.99	8.46	0.46	0.99	1.09	
Left Arm	10.64	0.59	1.00	13.58	0.73	0.98	1.32	
Left Foot	10.87	0.60	1.00	10.87	0.60	1.00	1.00	nude
Left Hand	14.76	0.59	1.00	15.11	0.68	0.98	1.00	nude
Left Leg	12.42	0.55	1.00	17.32	0.64	0.98	1.42	
Left Upper Arm	9.95	0.64	1.00	11.72	0.67	0.99	1.19	
Left Thigh	8.22	0.61	1.00	10.15	0.66	0.98	1.25	
Right Arm	11.02	0.63	1.00	11.00	0.67	0.95	1.02	
Right Foot	10.91	0.58	1.00	10.91	0.58	1.00	1.00	nude
Right Hand	12.58	0.63	1.00	12.58	0.63	1.00	1.00	nude
Right Leg	12.54	0.56	1.00	17.77	0.65	0.99	1.44	
Right Upper Arm	9.08	0.65	1.00	11.86	0.74	0.97	1.34	
Right Thigh	8.12	0.64	1.00	8.11	0.69	0.99	1.01	
Pelvic Region	9.24	0.59	1.00	12.81	0.59	0.94	1.40	
Whole Body	9.43	0.63	1.00	12.49	0.66	0.99	1.34	

for each part and the whole body. The model constants were defined as logarithmic functions (I_{cl} = a ln(v) +b). The constant 'a' for most of the segments was found between -0.01 and -0.26. For the whole body the constants were between -0.076 to-0.096. In absolute value, the constants for sitting were slightly larger than standing and the constants for frontal wind were slightly larger than the wind from the back.

(6) Comparison with other studies Figure 7 shows comparison of convective heat transfer coefficients for whole body with other studies. For standing posture, the present model for frontal wind were close to the deDear's and Nish&Gagge's models. When wind speed was in the range from 1.0 to 4.0m/s, our model was also close to the straight line for vertical plane from McAdams' model. Ichhara's and Seppanen's models gave very large value compared to the other nude data and those happened to be close to the present model for clothed standing manikin. On the other hand, for sitting manikin, the present model was close to deDear's model and fell between Winslow's and Mitchell's data.

Table 8 Models of clothing insulation for standing manikin

	Facing Upwind			Facing Downstream			
Body Segment	a	b	R^2	a	b	R^2	reference data
Back	-0.090	0.861	0.991	-0.141	0.820	0.976	
Chest	-0.136	0.917	0.936	-0.060	0.946	0.852	
Head	-0.240	0.642	0.982	-0.256	0.735	0.977	
Left Arm	-0.096	0.579	0.918	-0.074	0.538	0.947	
Left Foot	-0.037	0.647	0.890	-0.057	0.643	0.991	sitting
Left Hand	-	-	-	-	-	-	nude
Left Leg	-0.049	0.512	0.869	-0.042	0.516	0.700	sitting
Left Upper Arm	-0.097	0.566	0.910	-0.064	0.554	0.958	
Left Thigh	-0.072	0.480	0.983	-0.016	0.406	0.854	
Right Arm	-0.096	0.614	0.867	-0.079	0.576	0.889	
Right Foot	-0.038	0.633	0.912	-0.059	0.660	0.991	sitting
Right Hand	-	-	-	-	-	-	nude
Right Leg	-0.057	0.503	0.907	-0.041	0.524	0.748	sitting
Right Upper Arm	-0.101	0.563	0.960	-0.057	0.529	0.984	
Right Thigh	-0.055	0.419	0.832	-0.038	0.412	0.957	
Pelvic Region	-0.114	1.057	0.928	-0.102	0.970	0.836	
Whole Body	-0.090	0.632	0.977	-0.076	0.617	0.981	

Table 9 Models of clothing insulation for sitting manikin

	Facing Upwind			Facing Downstream			
Body Segment	a	b	R^2	a	b	R^2	reference data
Back	-0.050	0.839	0.765	-0.159	0.771	0.966	
Chest	-0.189	1.012	0.971	-0.105	1.073	0.936	
Head	-0.199	0.517	0.991	-0.246	0.625	0.991	
Left Arm	-0.066	0.499	0.727	-0.026	0.522	0.729	
Left Foot	-0.037	0.647	0.890	-0.057	0.643	0.991	nude
Left Hand	-	-	-	-	-	-	nude
Left Leg	-0.049	0.512	0.869	-0.042	0.516	0.700	
Left Upper Arm	-0.101	0.649	0.822	-0.083	0.696	0.760	
Left Thigh	-0.082	0.535	0.974	-0.037	0.464	0.909	
Right Arm	-0.077	0.552	1.000	-0.028	0.556	0.573	
Right Foot	-0.038	0.633	0.912	-0.059	0.660	0.991	nude
Right Hand	-	-	-	-	-	-	nude
Right Leg	-0.057	0.503	0.907	-0.041	0.524	0.748	
Right Upper Arm	-0.111	0.703	0.959	-0.094	0.703	0.980	
Right Thigh	-0.064	0.518	0.888	-0.008	0.387	0.292	
Pelvic Region	-0.152	1.004	0.889	-0.161	1.013	0.969	
Whole Body	-0.096	0.646	0.970	-0.088	0.655	0.986	

5. SUMMARY

Direct evaluation of clothing insulation and convective heat transfer coefficients for each part of the body under air flow was carried out by measuring surface temperature, using an infrared image radiometer. Larger convective heat transfer coefficients were observed for the clothed manikin than the nude manikin. The difference could be 100 to 200% for a few body parts. Over the whole body, the clothed manikin convective heat transfer coefficients were 30 to 50% larger than the nude manikin values. These results were consistent for both standing and sitting postures, and for facing either upwind or downstream, although a slightly larger difference between clothed and nude was seen when the manikin was sitting and facing upwind than in the other conditions.

In the clothing insulation for individual parts, some differences were observed between standing and sitting. However the difference for the whole body was small.

In addition, regression models for convection heat transfer under airflow condition were presented. The I_{cl} and h_{cl} estimated in this study includes

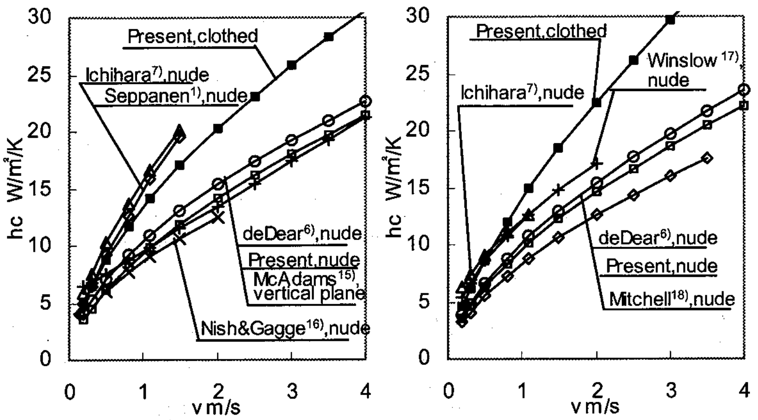


Figure 7 Comparison with other studies (Left: standing, Right: sitting)

the effect of heat loss by air penetration of the clothing, and therefore should be applied to only the types of clothing in this study. Similar studies of other clothing types would be needed to more generally describe heat transfer through the permeable complex clothing surface.

References

1)ASHRAE, ASHRAE HANDBOOK FUNDAMENTALS, 1997.

2) ISO9920, Ergonomics of the thermal environment -estimation of the thermal insulation and evaporative resistance of a clothing ensemble, 1995.

3) C. Lee, T. Sawachi, H. Honma: Experimental study on natural convection around human body using combined heated cylinder thermal manikin, Journal of Architectural Planning and Environmental Engineering, AIJ, No. 416, pp. 25-34, 1990.

4) S. Murakami, S. Kato, J. Zeng: Coupled simulation of convective and radiant heat transfer around standing human body, Journal of Architectural Planning and Environmental Engineering, AIJ, No. 515, pp. 69-74, 1999.

5) J. Ishii, T. Horikoshi, S. Watanabe, K Suzuki, Y. C. Zhi: Experimental estimation of natural convective heat transfer coefficients for the human body and its segments, Journal of Architectural Planning and Environmental Engineering, AIJ, No. 530, pp. 31-37, 2000.

6) R. deDear, E. Arens, H. Zhang, M. Oguro: Convective and radiative heat transfer coefficients for individual human body segments, International Journal of Bio meteorology, Vol. 40, No. 3, pp. 141-156, 1997.

7) M. Ichihara, M. Saitou, M. Nishimura, S. Tanabe: Measurement of convective and radiative heat transfer coefficients of standing and sitting human body by using a thermal manikin, Journal of Architectural Planning and Environmental Engineering, AIJ, No. 501, pp.45 ~51, 1997.

8) U. Danielsson: Convection coefficients in clothing air layers, Doctoral thesis in Department of Energy Technology, The Royal Institute of Technology, 1993.

9) M. Oguro, E. Arens, R. deDear, H. Zhang, T. Katayama: Evaluation of the effect of air flow on clothing insulation and on dry heat transfer coefficients for each part of the clothed human body, Journal of Architectural Planning and Environmental Engineering, AIJ, Nov. 2001.

10) B. Griffith, F. Beck, D. Arasteh, D. Türler: Issues associated with the use of infrared thermography for experimental testing of insulated systems, Proceedings of Thermal Performance of the Exterior Envelopes of Buildings Conference, 1995.

11) S. Tanabe, E. Arens, F. Bauman, H. Zhang, M, T. Madsen: Evaluating thermal environments using a thermal manikin with controlled surface skin temperature, ASHRAE Transactions, Vol. 100, 1994.

12) M. Oguro, E. Arens, H. Zhang, K. Tsuzuki, T. Katayama: Measurement of projected area factors for thermal radiation analysis on each part of the human body, to be published in Journal of Architectural Planning and Environmental Engineering, AIJ, Sept. 2001.

13) M. Oguro, E. Arens, H. Zhang, K. Tsuzuki, T. Katayama: Measurement of projected area factors for each part of a sitting person, to be published in Journal of Energy and Environmental Engineering, Kyushu University, Sept. 2001.

14) ISO9920, Ergonomics of the thermal environment -estimation of the thermal insulation and evaporative resistance of a clothing ensemble, 1995.

15) W.H. McAdams: Heat transmission, 3rd ed. McGraw-Hill, New York, 1954.

16) Y. Nishi, A.P. Gagge: Direct evaluation of convective heat transfer coefficient by naphthalene sublimation, Journal of Applied Physiology 29, 1970.

17) C. -E. A. Winslow, L. P. Herrington, A. P. Gagge: Relations between atmospheric conditions, physiological reavtions and sensations pf pleasantness, American Journal of Hygiene 26(1), 1937.

18) D. Mitchell: Convective heat transfer in man and other animals, heat loss from animals and man. Butterworth Publishing Inc., London, 1975.

和文要約

1.　はじめに

裸体人体については、部位別の対流熱伝達の研究例も多い。しかし、着衣人体について、有風時を対象として部位別の着衣表面での対流熱伝達率や着衣熱抵抗を測定した例は非常に少ない。

2.　研究方法

(1) 直接法による着衣熱抵抗の評価

人体各部の熱抵抗は (1) 式で表され、サーマルマネキンで熱量と皮膚温度が解っていれば、着衣の表面温度を測定することにより、着衣抵抗が直接算出できる。

(2) 対流熱伝達率の評価

サーマルマネキンにおける人体各部の熱損失は (2) (3) 式で表され、各部の総合熱伝達率から放射熱伝達率を差し引くことにより各部の対流伝達率が算出できる。

(3) 放射熱伝達率の評価

サーマルマネキンにおける人体各部の放射熱伝達率は (4) 式で表され、有効放射面積率より各部の放射熱伝達率が算出できる。

3.　計測方法

(1) サーマルマネキン

計測に用いたマネキンは皮膚温度可変型の女性体のサーマルマネキンで、主に室内の不均一温熱環境の評価用として開発されたものである。部位の分割数は 16 であり、表面積は表-1、有効放射面積率は表-2 のよう求められている。

(2) 着衣

計測に用いた着衣は下着、綿 100%の長ズボン、および綿100%の長袖シャツ、靴下、靴である。頭にはセミロングのかつらを取りつけ、着衣の一つとして評価した。また、人体各部の着衣からの熱損失量を明確にするため、マネキンの各部位の境界をビニールテープで縛り、着衣内での部位間の熱の移動がないよう配慮した。図-1 に写真を示す。

(3) 着衣面積率の計測

立位マネキンを対象とし、2m離れた位置から、裸体、着衣時の双方について、水平方向に 45° 毎に 8 方位から撮影し、投影面積の比を平均することにより着衣面積率を算出した。

(4) 風洞実験手順

風洞の測定部（高さ 1.5m、幅 2.1m）にマネキンを設置した。風洞上流側には、乱れをつくるための高さ 1m、直径 0.5mの円柱を測定部の上流 7mの位置に設置した。表面温度測定は、熱画像をマネキン正面と背面から測定した。熱画像を解析することにより、各部位の正面と背面の着衣表面温度を求め、それらを平均することにより各部位の着衣表面温度とした。実験条件としては、裸体および着衣のマネキンそれぞれについて、正面および背面から風を当てて測定した。設定風速は 0.2、0.5、0.8、1.2、2.0、3.0、5.5m/s（裸体では 0.8、2.0、5.5m/s のみ）である。

4.　結果および考察

(1) 着衣面積率

部位毎の着衣面積率を表-3 に示す。

(2) 立位の対流熱伝達率

図-2(a)(b)に立位での前方からの風および後方からの風の時の、裸体時と着衣時の対流熱伝達率を示す。裸体では、手の値が大きい。着衣時は全般的に裸体時より大きくなる傾向がある。特に頭や風に対抗した時の胸や背中では裸体時の 2 倍以上になる。0.8 m/s 程度ではその差は小さいが、風速が大きくなるに従い、その差は大きくなる傾向にある。その差は正面からの風の時の頭が最も大きい。その他の部位では正面からの風の時の胸、および背後からの風の時の背中での差が他の部位に比べると大きい。

(3) 座位の対流熱伝達率

図-3(a)(b)に座位の対流熱伝達率お結果を示す。着衣時については、立位と同様裸体時より大きくなる傾向がみられる。着衣時については、立位と同様裸体時より大きくなる傾向がみられる。立位との主な差異は、前方からの風で大腿での裸体時との差が大きい点と、後方からの風の時に頭の裸体時との差が小さい点である。全身の値で比較すると裸体時、着衣時とも、立位と座位、あるいは前方からの風と後方からの風で大きな差はみられない。一方、着衣時の値は裸体時より 30～50%大きい。

(4) 着衣熱抵抗

着衣熱抵抗の測定結果を図-5、6 に示す。前方からの風での部位別（図-5）では、大腿、胸、上腕では座位の方が熱抵抗が高く、腰、頭、前腕では座位の方が低い。全身（図-6）の値で比較すると立位と座位で大きな差はみられない。

(5) 対流熱伝達率と着衣熱抵抗のモデル

表-4～7 に対流伝達率のモデルを示す。モデルはべき乗則($h_c = a(v)^b$)で近似される。部位別ではべき指数 b が 0.4～0.8 とばらつく。全身ではべき指数 0.60～0.69 と立位と座位、風向、裸体と着衣で大きな差はない。対流熱伝達の裸体と着衣の差は主に定数 a に反映されている。着衣熱抵抗のモデルを表-8、9 に示す。モデルは対数則($I_{cl} = a \ln(v) + b$)で近似される。部位別では定数 a が-0.01～-0.26 とばらつく。全身では-0.076～-0.096 と立位と座位、風向、裸体と着衣で特に大きな差はない。

5. まとめ

有風時の部位別の着衣抵抗と着衣表面の対流熱伝達率を着衣の表面温度計測により求めた。着衣時は裸体時に比較して対流熱熱伝達率の増大が認められた。また、部位別および全身について対流熱伝達率と着衣抵抗の近似モデルを示した。本論文で求めた対流熱伝達率や着衣抵抗は通気の影響を含むものであり、同タイプの着衣にのみ適用すべきである。

(2001年10月10日原稿受理，2002年 8 月27日採用決定)